# Status, perspectives, and lessons from FLASH and European XFEL

R. Brinkmann, E.A. Schneidmiller, J, Sekutowicz, H. Weise, M.V. Yurkov

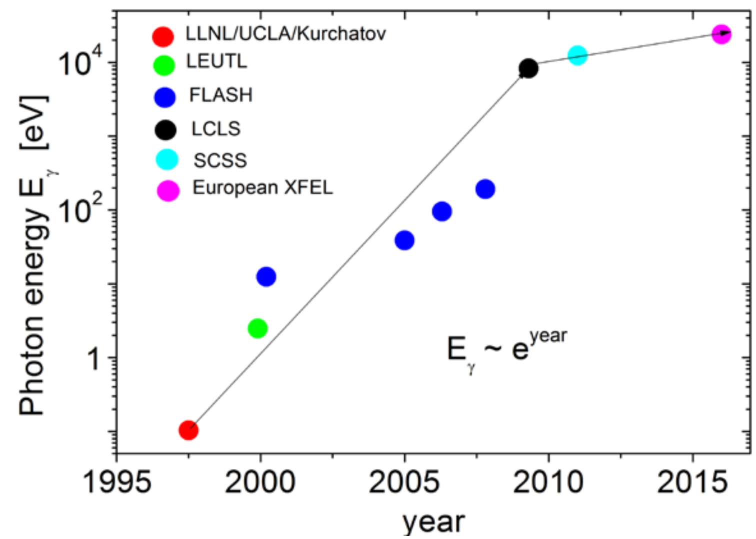
DESY, Hamburg

- FLASH and European XFEL.
- Scaling of the burst mode for high average power at 13.5 nm and 6.8 nm.
- CW option and scaling of CW mode for high average power NGL source.

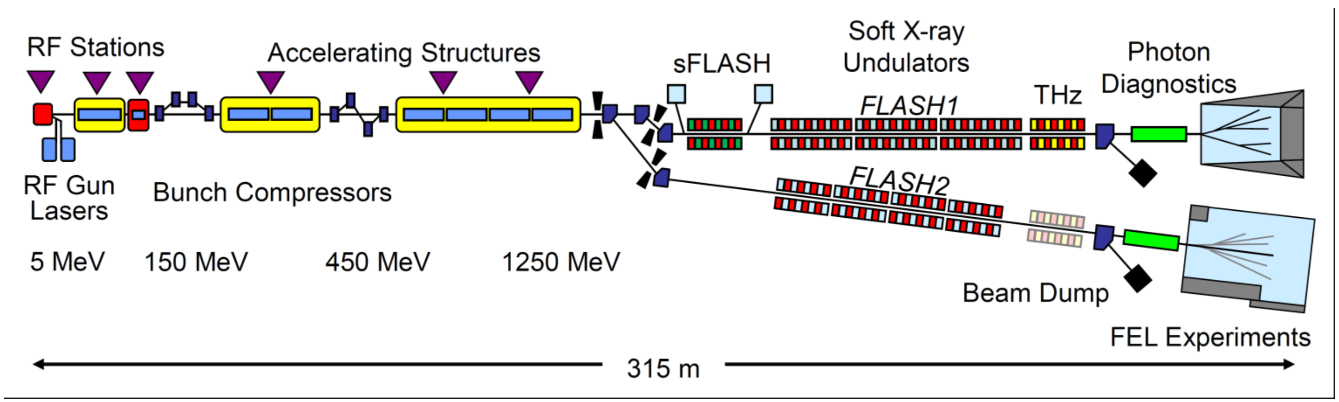
# DESY areal view

# Experience from FLASH, TESLA, and ILC

FLASH (Free-electron -LASer in Hamburg) is a superconducting linear accelerator with free electron laser for radiation in the vacuum-ultraviolet and soft X-ray range of the spectrum. It originated from the TTF (TESLA Test Facility), which was built in 1997 to test the technology that was to be used in the planned linear collider TESLA, a project which was replaced by the ILC (International Linear Colider). At FLASH technology for the future-project European XFEL is tested as well as for the ILC. Five scientific instruments have been in use since the commissioning of the facility in 2004. Second stage, FLASH 2 is under commissioning now. First lasing has been obtained in August, 2014.

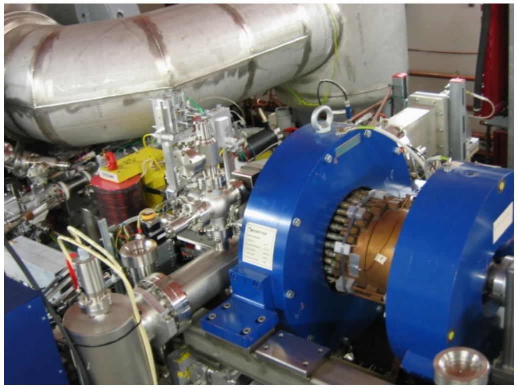



- FLASH was leading SASE FEL facility during last decade.




# Elements of FLASH free electron laser

FLASH consists of the same elements as European XFEL

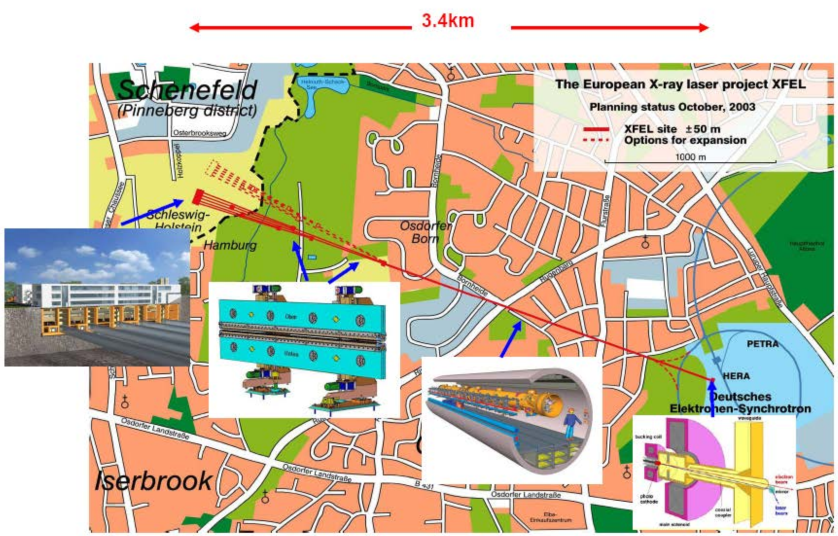


Laser-driven rf gun



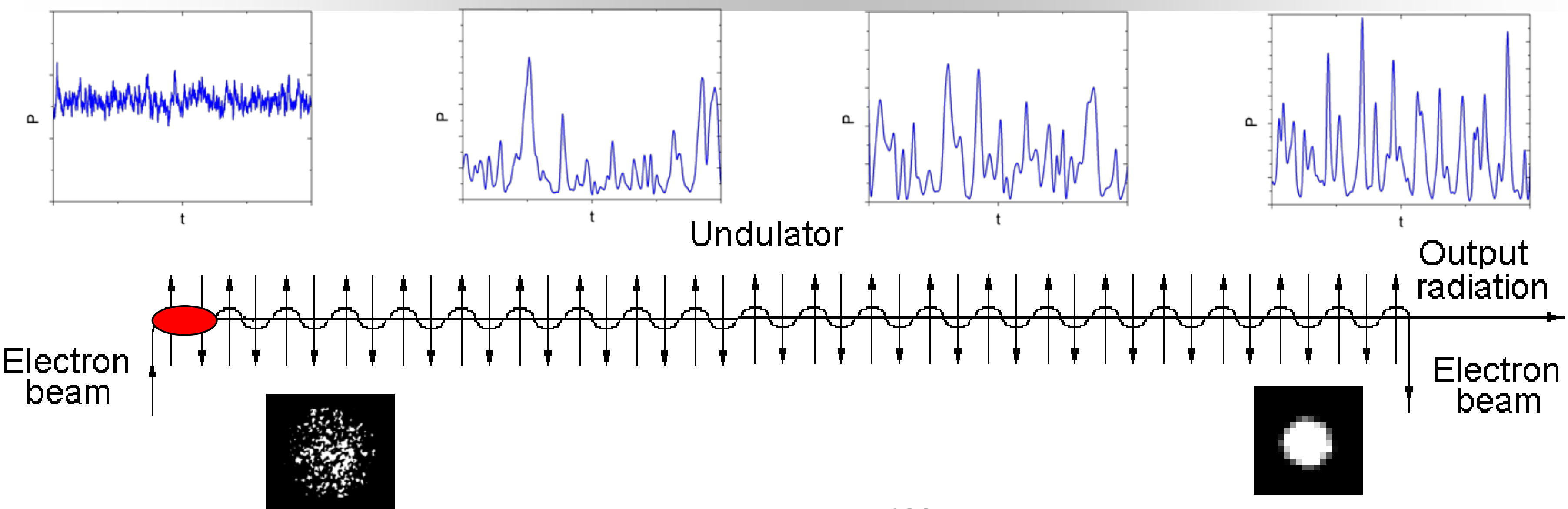
Superconducting accelerator

FLASH1 and FLASH2 undulators

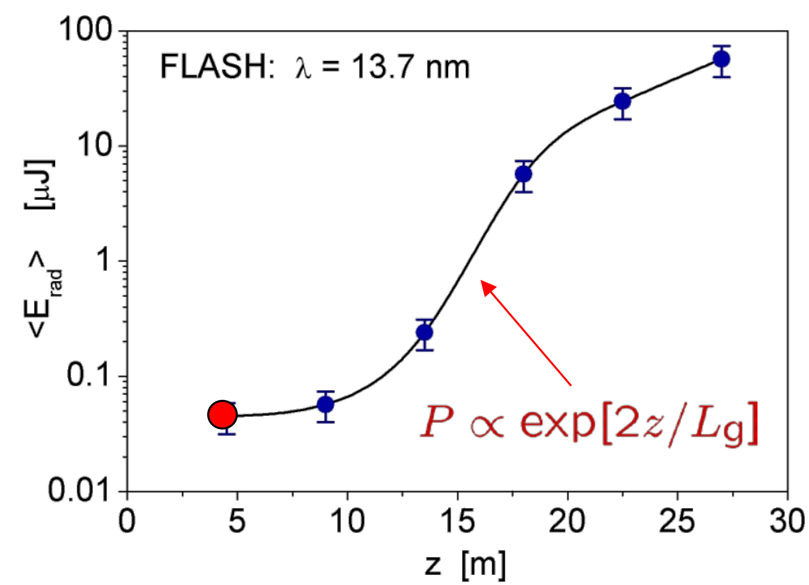




# Self-Amplified Spontaneous Emission (SASE) FEL
# (single pass FEL amplifier starting from shot noise)




- The physics of SASE FEL (single-pass FEL amplifier starting from shot noise) is well understood and demonstrated experimentaly at many facilities.
- FLASH facility provided outstanding experience in the EUV and soft x-ray wavelength range.

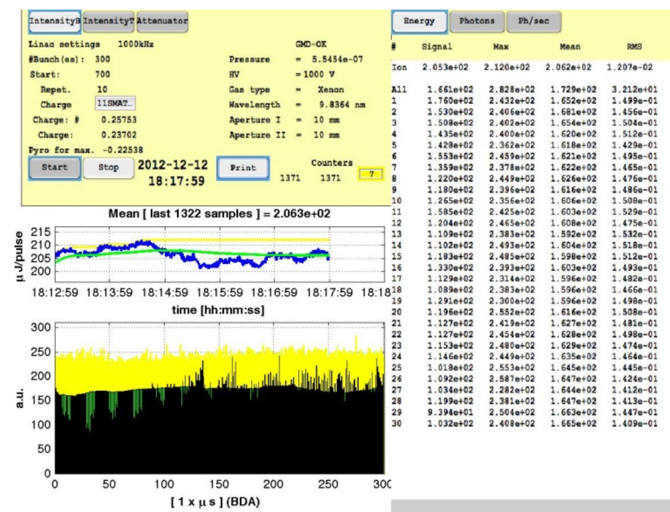




Ya.S. Derbenev, A.M. Kondratenko, E.L. Saldin, NIM 193(1982)415
W. Ackermann et al., Nature Photonics, 1 (2007) 336

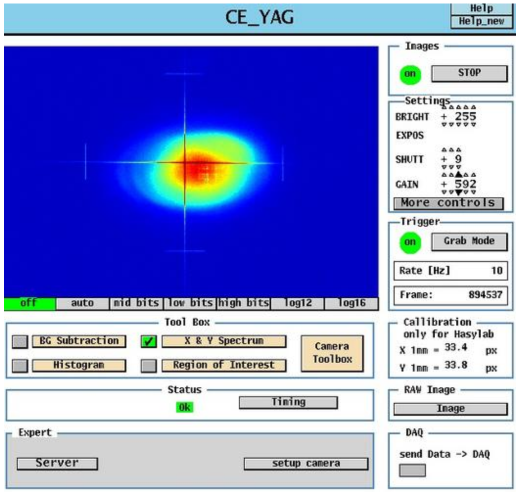
# FLASH parameters

| | |
|---|---|
| Electron energy | up to 1250 MeV |
| Bunch charge | 20 pC – 1 nC |
| Repetition rate | 10 Hz |
| Pulse duration | 0.8 ms |
| Micropulse rep. rate | 0.1 – 9 MHz |
| Wavelength Range | 4.2 - 45 nm |
| Average Single Pulse Energy | 10 - 500 µJ |
| Pulse Duration (FWHM) | <50 - 200 fs |
| Peak Power (from av.) | 1 - 3 GW |
| Average Power (example for 3000 pulses/sec) | up to 600 mW |
| Spectral Width (FWHM) | 0.7 - 2 % |
| Photons per Pulse | $10^{11}$ - $10^{13}$ |
| Average Brilliance | $10^{17}$ - $10^{21}$ ph./s/mrad$^2$/mm$^2$/0.1%bw |
| Peak Brilliance | $10^{29}$ - $10^{31}$ ph./s/mrad$^2$/mm$^2$/0.1%bw |

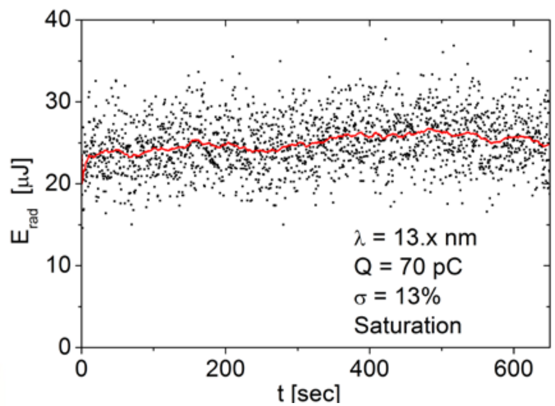



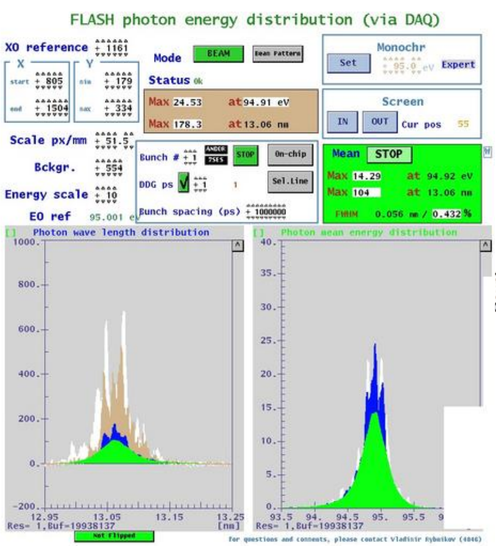

K. Honkavaara, B. Faatz, J. Feldhaus, S. Schreiber, R. Treusch, M. Vogt, Status of the FLASH Facility, Proc. FEL2013 Conference, New York, USA, 2013, wepso26. http://accelconf.web.cern.ch/AccelConf/FEL2013/papers/weps026.pdf

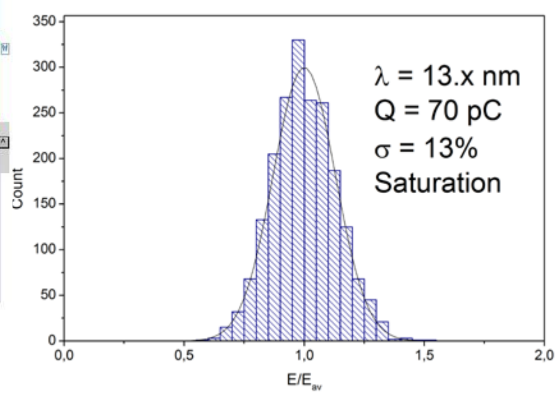
# FLASH at 13.x nm (small charge)




| 11.01.2013 17:24 | Schneidmiller/Yurkov | Statistical measurements with MCP detector and spectral measurements - summary |
|---|---|---|




Statistical run for linear regime. SASE has been killed after 4 undulator modules.

Data files for linear regime:

.. 17_19_29.mcp
.. 17_19_30.mcp

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Summary of the results

Radiation wavelength: 13.06 nm
Fluctuations in the linear regime: 42%.
Number of modes: M = 5.7
Fluctuations in saturation: 13%.
Saturation length: Lsat ~= 22 m
Angular divirgence in saturation (FWHM): ~ 40 urad.
Spectrum bandwidth in the linear regime (FWHM): 0.35%
Spectrum bandwidth in the saturation regime (FWHM): 0.42%

Radiation pulse length in the linear regime:

L = (M x radiation wavelength x Saturation length ) / (5 x Undulator period) ~= 40 fs (FWHM)

Radiation pulse duration at full undulator length is estimated as 50 fs.

rms bunch length of lasing fraction of the electron beam: 40 fs. Assuming gaussian shape of the electron bunch we get an estimate for the peak current I ~= 700 A. These parameters are consistent with measured properties of the radiation if rms normalized emittance is below 1 mm-mrad. Scenarios with deviation from gaussian shape can be discussed later.

Spectrum bandwidth of the radiation is pretty close to that generated by monochromatic electron beam (natural SASE bandwidth). Thus, lasing part of the beam is not disturbed by chirp (due to beam formation procedure or collective effects).

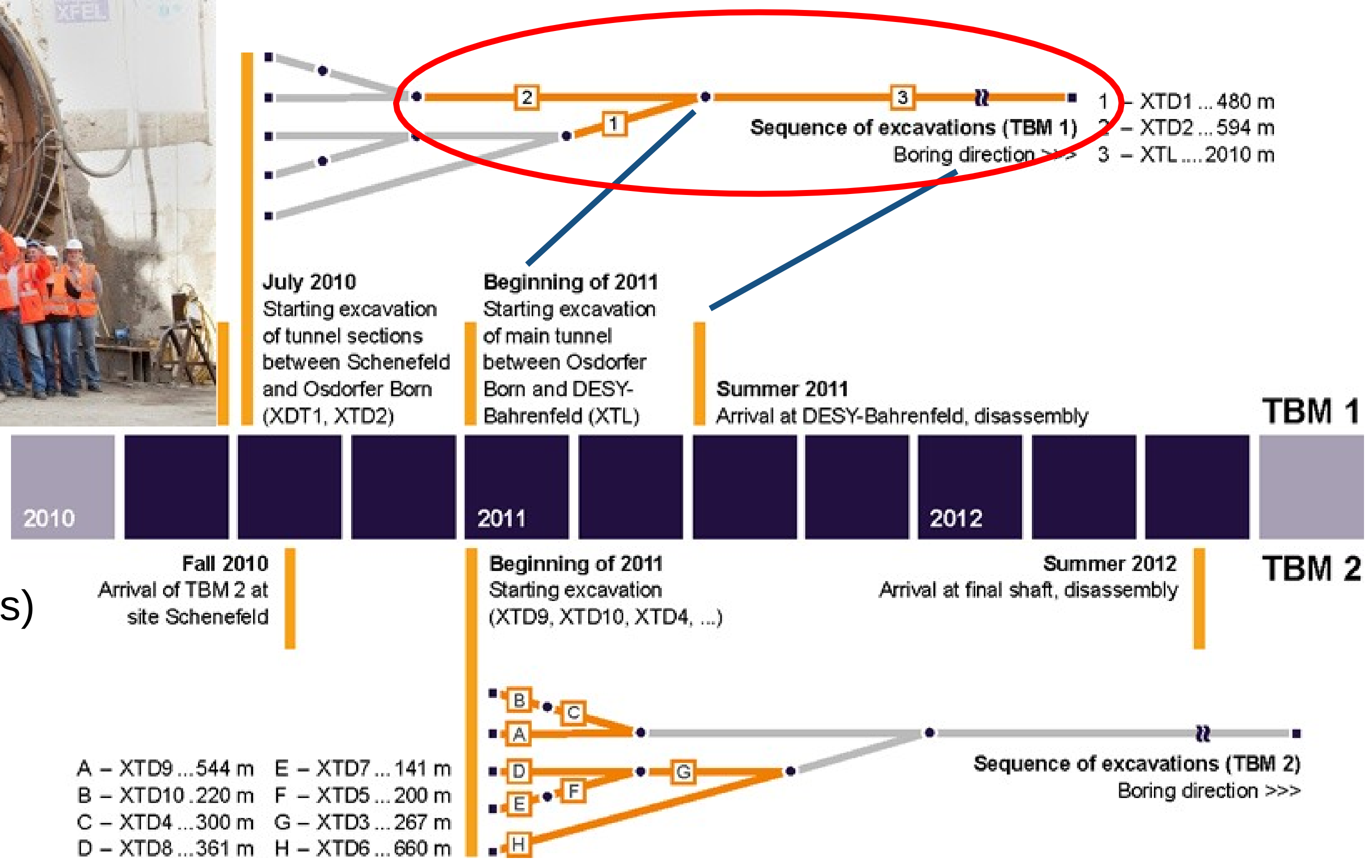

J. Roensch-Schulenburg, E. Hass, A. Kuhl, T. Plath, M. Rehders, J. Rossbach, G. Brenner, C. Gerth, U. Mavric, H. Schlarb, E. Schneidmiller, S. Schreiber, B. Steffen, M. Yan, M.V. Yurkov, Short SASE-FEL Pulses at FLASH, Proc. FEL2013 Conference, New York, USA, 2013, tupso64. http://accelconf.web.cern.ch/AccelConf/FEL2013/papers/tupso64.pdf

# European XFEL: present status

Underground construction is finished in 2012.

Installation of equipment is going on.

Start of operation: 2016.




Start-up configuration:

17.5 GeV

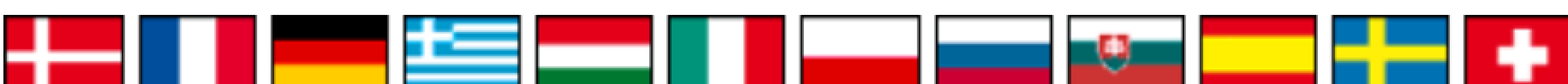
Burst mode (10 Hz x 0.6 ms)

27000 pulses per second

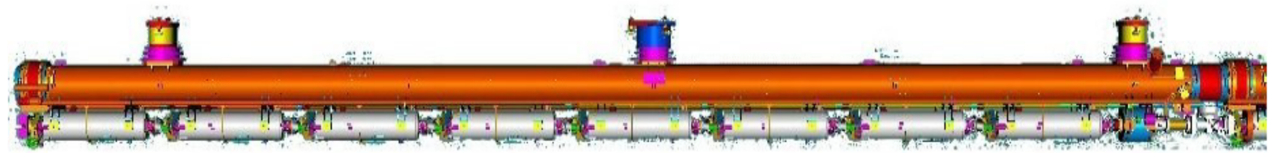
3 undulators

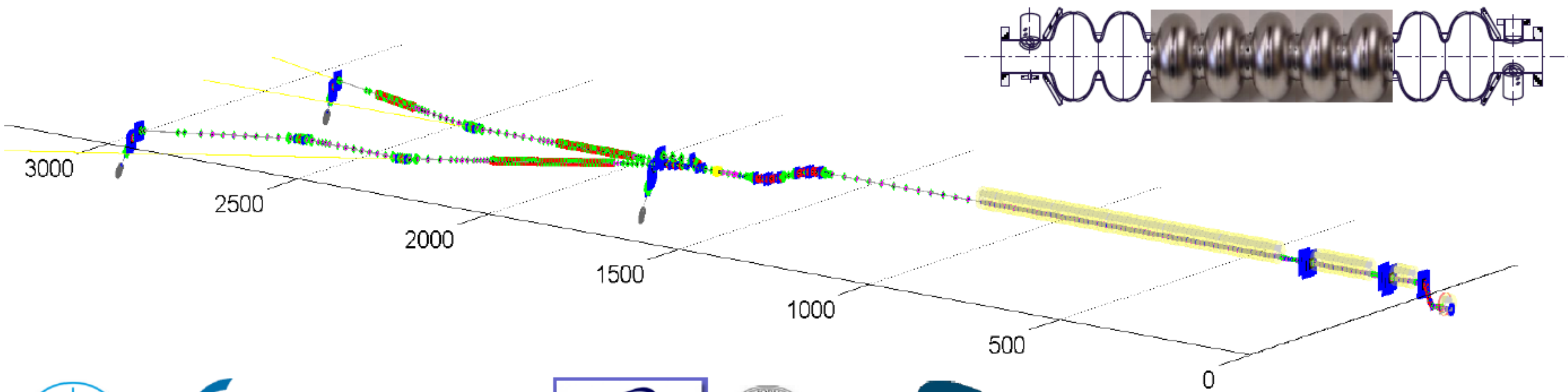
0.05nm – 5 nm

6 user stations



# European XFEL: Accelerator consortium



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Wrocław University of Technology
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UPPSALA UNIVERSITET
PAUL SCHERRER INSTITUT PSI

H. Weise, Proc. IPAC2014 Conference, weib03,
http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/weib03.pdf

DESY

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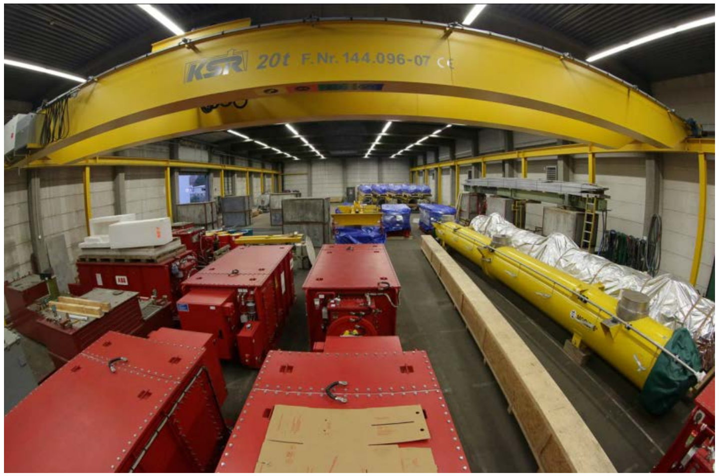
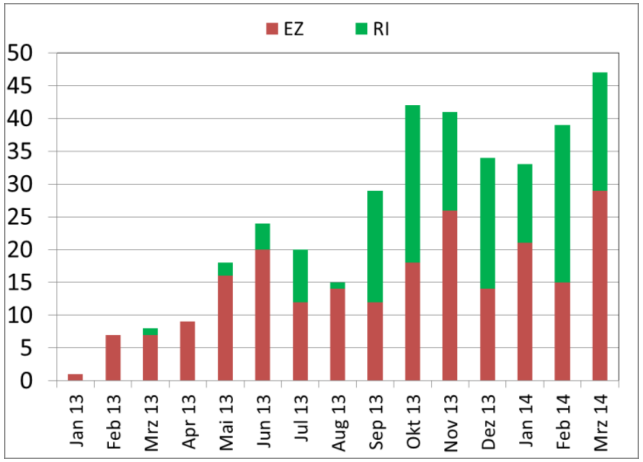
# European XFEL: Industrial production of accelerator components and undulators

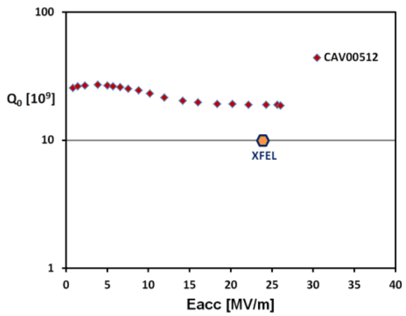




H. Weise, Proc. IPAC2014 Conference, weib03,
http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/weib03.pdf

# DESY: Very successful transfer of SRF technology from laboratory to industry in the framework of XFEL project



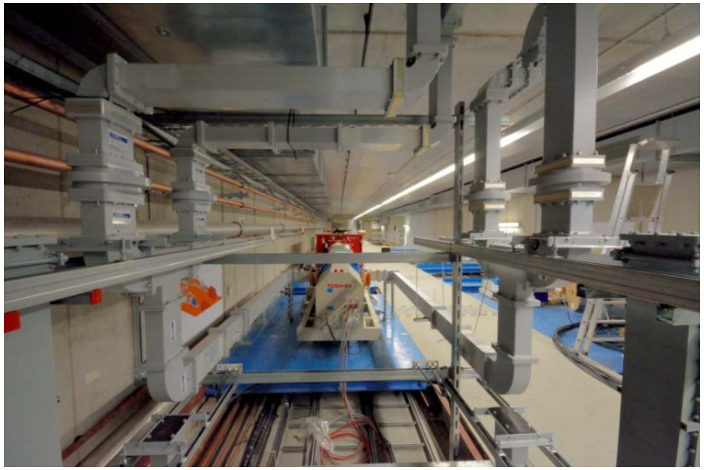




| | 25.10.13 | | | as received | | after re-treatment | |
|---|---|---|---|---|---|---|---|
| | data analyzed | accepted w/o re-treatment | re-treatment done / to be done | Emax | usable gradient | Emax | usable gradient |
| Zanon | 67 | 40 | 18 / 9 | (27,7 +- 7,5) MV/m | (24,4 +- 7,3) MV/m | (30,0 +- 5,0) MV/m | (27,6 +- 5,1) MV/m |
| RI | 46 | 32 | 5 / 9 | (32,6 +- 7,1) MV/m | (27,7 +- 7,1) MV/m | (34,3 +- 4,8) MV/m | (30,4 +- 4,4) MV/m |

- average delivery of 8 cavities per week reached
- in total more than 400 cavities delivered until mid-2014
- Very few non-conformities, i.e. some rejected cavities
- re-treatment (mostly only HPR) successful and done for all cavities showing some gradient potential, i.e. even if European XFEL specs. are met

## Accelerating module

## rf gun and multi-beam klystron

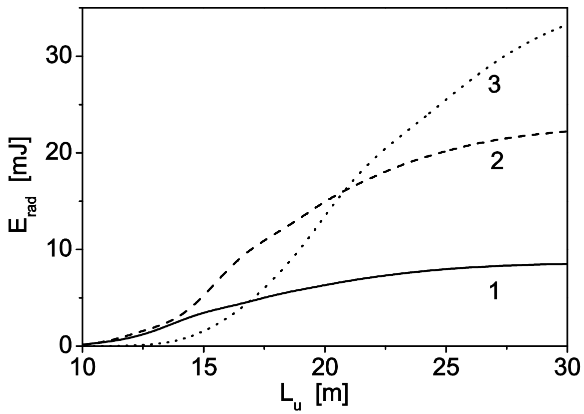


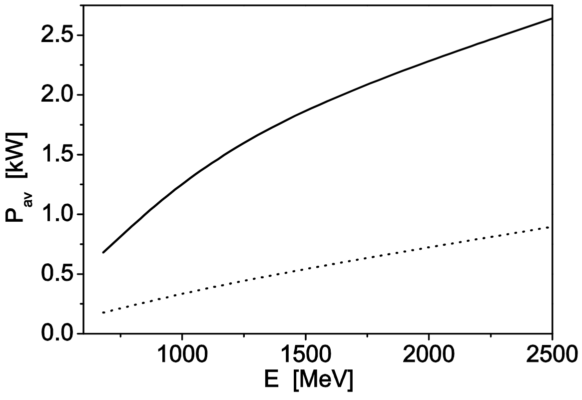


H. Weise, Proc. IPAC2014 Conference, weib03,
http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/weib03.pdf

# FLASH technology: scaling of burst mode to high average power 13.5 nm NGL source

| | FLASH | NGL-680 | NGL-1250 | NGL-2500 |
|---|---|---|---|---|
| Electron energy, MeV | 680 | 680 | 1250 | 2500 |
| Bunch charge, nC | 1 | 1 | 1 | 1 |
| Peak current, A | 2500 | 2500 | 2500 | 2500 |
| Normalized emittance, mm-mrad | 1.5 | 1.5 | 1.5 | 1.5 |
| rms energy spread, MeV | 0.5 | 0.5 | 0.5 | 0.5 |
| Macropulse duration, ms | 0.8 | 0.8 | 0.8 | 0.8 |
| Micropulse rep. rate, MHz | 9 | 10 | 10 | 10 |
| # pulses in macropulse | 7200 | 8000 | 8000 | 8000 |
| Macropulse rep. rate, Hz | 10 | 10 | 10 | 10 |
| Undulator period, cm | 2.73 | 2.73 | 3.7 | 5.0 |
| Undulator length, m | 27 | 30 | 30 | 30 |
| Energy in the radiation pulse, mJ | 1.4 | 8.5 | 22 | 33 |
| Peak power, GW | 5.6 | 34 | 88 | 130 |
| Average radiation power, W | 100 | 680 | 1760 | 2640 |

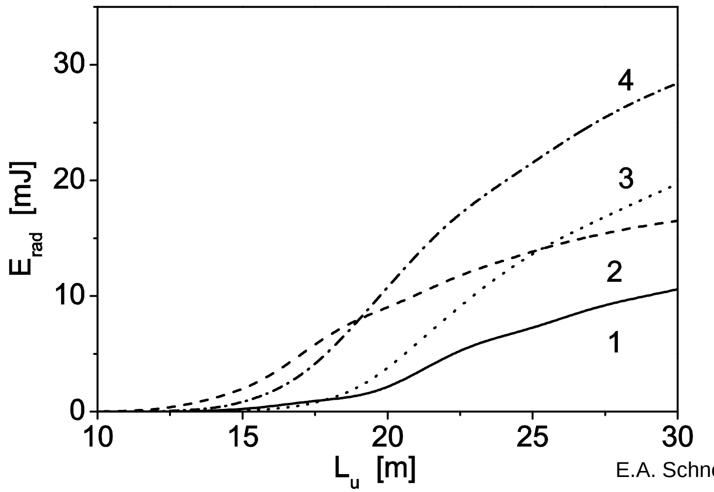



E.A. Schneidmiller, V.F. Vogel, H. Weise and M.V. Yurkov, Journal of Micro/Nanolithogrphy, MEMS, and MOEMS 11(2), 021122 (2012).

# FLASH technology: scaling of burst mode to high average power 6.8 nm NGL source

| | | | | |
|---|---|---|---|---|
| Electron energy, MeV | 1250 | 1250 | 2500 | 2500 |
| Bunch charge, nC | 1 | 1 | 1 | 1 |
| Peak current, A | 2500 | 2500 | 2500 | 2500 |
| Normalized emittance, mm-mrad | 1.5 | 1 | 1.5 | 1 |
| rms energy spread, MeV | 0.5 | 0.5 | 0.5 | 0.5 |
| Macropulse duration, ms | 0.8 | 0.8 | 0.8 | 0.8 |
| Micropulse rep. rate, MHz | 10 | 10 | 10 | 10 |
| # pulses in macropulse | 8000 | 8000 | 8000 | 8000 |
| Macropulse rep. rate, Hz | 10 | 10 | 10 | 10 |
| Undulator period, cm | 3.7 | 3.7 | 5.0 | 5.0 |
| Undulator length, m | 30 | 30 | 30 | 30 |
| Energy in the radiation pulse, mJ | 11 | 16 | 20 | 28 |
| Peak power, GW | 44 | 64 | 80 | 110 |
| Average radiation power, W | 880 | 1280 | 1600 | 2240 |




E.A. Schneidmiller, V.F. Vogel, H. Weise and M.V. Yurkov,
Journal of Micro/Nanolithogrphy, MEMS, and MOEMS 11(2), 021122 (2012).

Two scenarios for the DF upgrade of XFEL

1. Lower cost scenario; the injector section stays as for the nominal operation and DFs < 20-25%.
2. Higher cost scenario; the injector section will be equipped with new cw-cavities and 12 present CMs will be moved to the end of ML.

| *Facility* | *Operation mode* | *Energy [GeV]* | *Eacc ML [MV/m]* | *RF-pulses Length [ms]* | *RF-pulses Rep. Rate [Hz]* | *Max DF [%]* |
|---|---|---|---|---|---|---|
| *LCLS* | *pulse* | *14.7* | | *0.003* | *120* | *0.036* |
| *SACLA* | *pulse* | *8* | | *0.003* | *60* | *0.018* |
| *Swiss-FEL* | *pulse* | *5.8* | | *0.003* | *100* | *0.03* |
| *XFEL* | *sp* | *17.5* | | *1.380* | *10* | *1.38* |
| *XFEL* | *cw* | *7.6* | *7* | *-* | *-* | *100* |
| *XFEL* | *lp* | *10* | *10* | *560* | *1* | *56* |
| *XFEL* | *lp* | *14* | *15* | *250* | *1* | *25* |

J. Sekutowicz et al., Proc. FEL2013 Conference, tuocn04, http://accelconf.web.cern.ch/AccelConf/FEL2013/papers/tuocno04.pdf

**New operation modes require a cw operating electron injector**

- **R&D activity in collaboration between: JLab, BNL, SLAC, HZB, NCNR, DESY.**
- **Our goal is a 1 mA-class SRF photoinjector with a superconducting cathode.**
- **Pb cathode ($T_c$ = 7.2 K, $B_c$ = 80 mT) was proposed in 2005.**

J. Sekutowicz et al., Proc. IPAC2013 Conference, tupea003, http://accelconf.web.cern.ch/AccelConf/IPAC2013/papers/tupea003.pdf

Talk at Accelerator-IMSS-AAT Joint Seminar: LCLS-II project at SLAC, 2014-04-14

## LCLS-II SRF Linac

Closely based on the *European XFEL / ILC / TESLA* Design

LCLS-II Linac consists of:

| Component | Count | Parameters |
|---|---|---|
| Linac | 4 cold - segments | 35 each 8 cavity Cryomodules (1.3 GHz)<br>3 each 4 cavity Cryomodules (3.9 GHz) |
| 1.3 GHz Cryomodule | 8 cavities/ CM | 13 m long. Cavities + SC Magnet package<br>+ BPM |
| 1.3 GHz 9-cell cavity | 280 each | 16 MV/m; Q_0 ~ 2.7e10 (avg); 2 deg. K; bulk niobium fine-grain sheet-metal |
| Cavity Auxiliary | per each cavity | Coaxial Input Coupler; 2 each HOM extraction coupler; lever-type tuner |
| Injector | 1 each | 1 each special cryomodule (TBD) |

A-I-A Joint Seminar 140414 M. Ross 2

J. Galayda, Proc. IPAC2014 Conference, tuoca01, http://accelconf.web.cern.ch/AccelConf/IPAC2014/papers/tuoca01.pdf

# FLASH technology: scaling of cw mode to high average power NGL source

ELSEVIER
Nuclear Instruments and Methods in Physics Research A 463 (2001) 9–25
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A
www.elsevier.nl/locate/nima

## Design considerations of 10 kW-scale extreme ultraviolet SASE FEL for lithography

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**Abstract**

The semiconductor industry growth is driven to a large extent by steady advancements in microlithography. According to the newly updated industry roadmap, the 70 nm generation is anticipated to be available in the year 2008. However, the path to get there is not obvious. The problem of construction of Extreme Ultraviolet (EUV) quantum laser for lithography is still unsolved: progress in this field is rather moderate and we cannot expect a significant break through in the near future. Nevertheless, there is clear path for optical lithography to take us to sub-100 nm dimensions. Theoretical and experimental work in free electron laser (FEL) and accelerator physics and technology over the last 10 years has pointed to the possibility of generation of high-power optical beams with laser-like characteristics in the EUV spectral range. Recently, there have been important advances in demonstrating a high-gain self-amplified spontaneous emission (SASE) FEL at 100 nm wavelength (Andruszkov et al., Phys. Rev. Lett. 85 (2000) 3825). In the SASE FEL powerful, coherent radiation is produced by the electron beam during single-pass of the undulator, thus there are no apparent limitations which would prevent operation at very short wavelength range and to increase the average output power of this device up to 10 kW level. The use of superconducting energy-recovery linac could produce a major, cost-effective facility with wall plug power to output optical power efficiency of about 1%. A 10-kW-scale transversely coherent radiation source with narrow bandwidth (0.5%) and variable wavelength could be an excellent tool for manufacturing computer chips with the minimum feature size below 100 nm. All components of the proposed SASE FEL equipment (injector, driver accelerator structure, energy-recovery system, undulator, etc.) have been demonstrated in practice. This is guaranteed success in the time schedule requirement. 

C. Pagani et al. / Nuclear Instruments and Methods in Physics Research A 463 (2001) 9–25

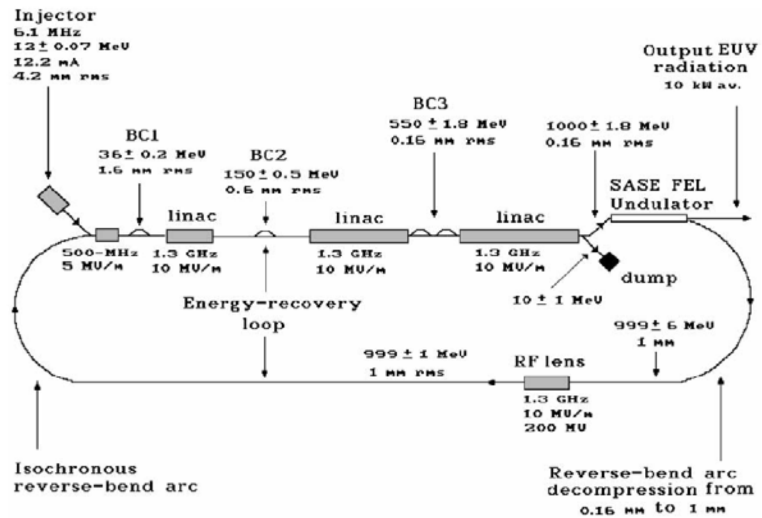


Fig. 2. Basic scheme of the high-power EUV SASE FEL.

ERL scheme similar to that of the year 2000 can be used. Key features of the proposal:

- CW injector.
- Superconducting CW energy recovery linac (1 GeV, 10 mA average current).
- Self-amplified spontaneous emission (SASE) FEL as radiation source (EUV, 10 kW average power).
- Application of the undulator tapering will allow to reduce average beam current, or to increase output power.

C. Pagani, E.L. Saldin, E.A. Schneidmiller, M.V. Yurkov, Nucl. Instrum. And Methods A 463 (2001) 9.

# Summary

- SRF accelerator technology and SASE FELs are developed at DESY for 20 years in the framework of TESLA/FLASH/XFEL/ILC projects.
- Both, burst and cw options reached mature status. 17.5 GeV linac for the European XFEL is being built using burst technology. CW option developed at DESY will form base for construction of 4 GeV cw linac at LCLS-II.
- All elements of the accelerators are produced by industry. An experience stored during construction of the European XFEL provides solid base for estimation of the cost of future industrial high power accelerators.
- The physics of SASE FEL is well understood, and experimental results are in good agreement with theoretical predictions. However, undulator tapering still requires more experimental experience. Relevant studies are planned to be performed at FLASH2.
- Both, burst and cw options allows to construct high average power (multi-kW) FEL as a source for the next generation lithography.
- The main concern of the future developments of high power systems is reliable prediction of the electron beam properties taking into account different physical effects like nonlinearities of collective fields, coherent synchrotron radiation, and space charge. While we can safely scale the output power to higher levels, the problem of beam halo seems to be an issue.

# Acknowledgments

The authors are grateful to all members of FLASH/ILC Team for fruitful collaboration.